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Environmentally Friendly Lubricants

by Alfred D. Beitelman, U.S. Army Construction Engineering Research Laboratories

The field of environmentally friendly lubricants (EFLs) is relatively new. It probably originated in the Black Forest of Europe in 1985 when power saw chains were required to be lubricated with such products. As time passes, the lubricants used in most logging, farming, construction, and earthmoving equipment are changing to meet environmentally friendly requirements. Today U.S. manufacturers and users are becoming increasingly interested in EFLs, as evidenced by the number of manufacturer representatives on the

American Society for Testing and Materials (ASTM) committees and the number of Corps Districts that have considered their use. Unfortunately, this interest has not translated into heavy EFL use.

While the user may encounter a number of problems when switching to or using EFLs, the real impediment appears to be more fundamental: what is an environmentally friendly lubricant? The term is not recognized by any U.S. environmental regulation, so any EFL spill must be reported and treated as if it were toxic material.

Even the industry does not agree on a meaning. It is generally assumed that EFLs must not be toxic and must biodegrade in a relatively short time, but no consensus has been reached on testing methods. What organisms should be used for the toxicity tests? And what should be the test duration or the required percentage of biodegradation? This biodegradability requirement means that EFLs are not the same as food-grade lubricants that meet certain toxicity requirements for human beings, but may be toxic to other land or aquatic life. The rating does not mean that the products will break down if released into the environment.

Work is underway in ASTM committees to develop standards that may resolve these deficiencies. Until the deficiencies are resolved, however, many potential manufacturers are delaying developmental work. Once a clear definition is established, perhaps Federal or State Environmental Protection Agency (EPA) regulations will be

enacted to provide incentives for using EFLs.

Manufacturers of EFLs do exist. The products do exist. Users do exist. The market is not dead. The highest volume of EFL products is in hydraulic fluids. Most of these products are based on rapeseed oil (RC) also known in the food industry as canola. (The rape plant is a member of the mustard family.) Other crop oils, synthetic esters (SEs), and polyglycols (PGs) are also being marketed. Most have excellent lubricating properties — in some cases superior to mineral oils — making them candidates for use not only as hydraulic fluids but also for lubricating oils and greases.

EFLs would be ideal if they had physical properties identical to the currently used mineral-based products, but such is not the case. Costs are higher, and compatibility with existing mineral-based products, moisture, and seal materials must be considered. EFLs typically have flatter viscosity curves but may also have more restrictive low- and high-temperature limits. No industry standards exist, so engineers desiring to use an EFL must consider each specific application and each specific product individually.

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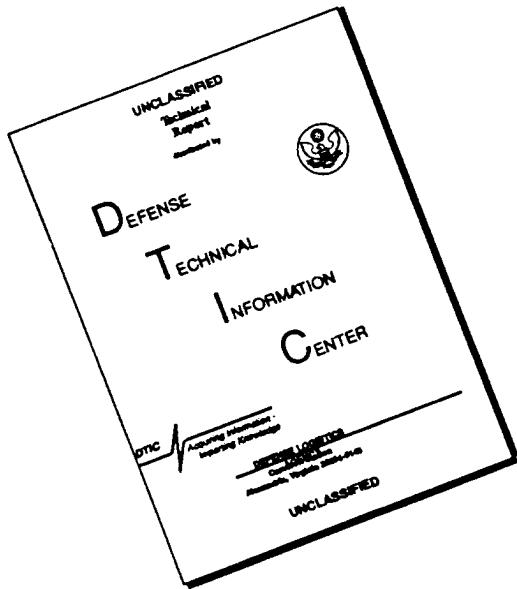


Gate lift system on power dam in Vermont.
Some environmentally friendly lubricants
perform very well at low temperatures



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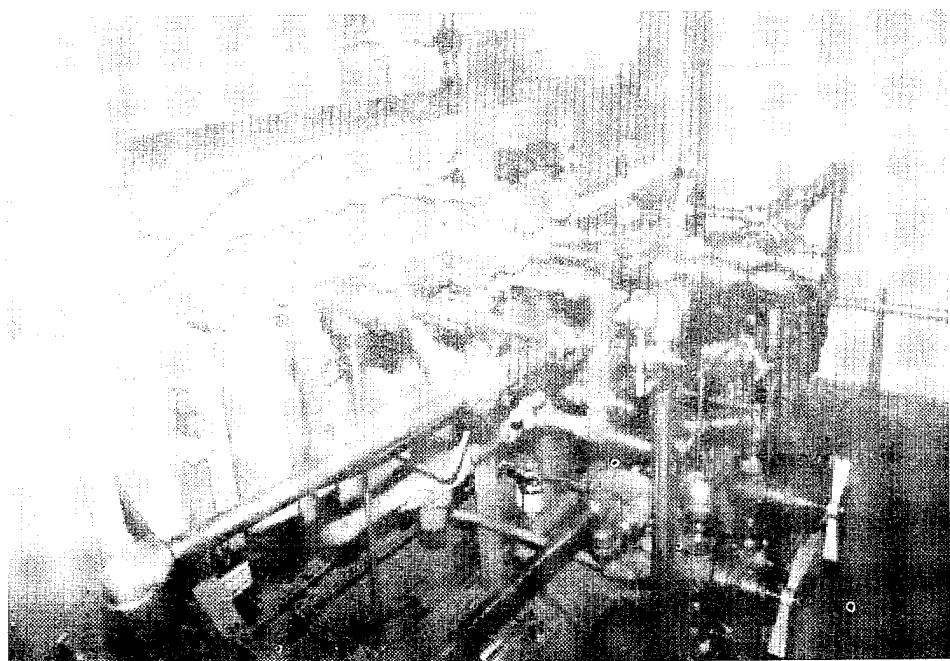
Polyglycol lubricants

PG hydraulic fluids have been available for several decades and are widely used, particularly in the food-supply industry. PGs also have been used for about 20 years in construction machinery (primarily excavators) and a variety of stationary installations. They were the first biodegradable oils on the market.

PG fluids have the greatest stability with a range from -45 °C to 250 °C and can have biodegradability up to 99 percent (Cheng et al. 1991). Oil-change intervals are similar to those for a mineral oil: 2,000 hr or once a year.

PG oils are not compatible with mineral oils and may not be compatible with common coatings, linings, seals, and gasket materials. They must be stored in containers free of linings. Some oils do not biodegrade well. The rate and degree of biodegradation are controlled by the ratio of propylene to ethylene oxides, with polyethylene glycols being the more biodegradable. The rate and extent diminish with increasing molecular weight.

When a hydraulic system is converted from mineral oil to PG, it is essential that the oil supplier's recommendations are followed. Normally, total system evacuation and one or two flushing procedures are required to avoid any mix with previously used mineral oil. Mineral oil is less dense than PG fluids, so any residual mineral oil will float to the top and must be skimmed off. According to the manufacturer's recommendations, the final residual quantity of mineral oil may not exceed 1 percent of the total fluid volume. Mineral oil must not be used to replace lost PG fluid, and other contamination of PG with mineral oil must be avoided. Compatibility with varnish, seal, and filter materials also must be considered. Paper filters may need to be replaced with glass-fiber or metal-mesh filters, which should be checked after the first 50 hr of operation. The filters will retain any residual mineral oil and may become clogged. Because of their excellent wetting properties, PG fluids tend to remove deposits left from operation with mineral oil, and these deposits are carried to the filter. Polyglycols are soluble in water, so water must be excluded from the system.



Pump system for environmentally friendly lubricants. All piping and the reservoir are of stainless steel to eliminate corrosion without the use of coatings

Synthetic esters

Synthetic esters are made from modified animal fat and vegetable oil. While there are similarities between RO and SEs, there are important differences. The esters are more thermally stable, and because of their higher proportion of single double bonds, the SE has enhanced oxidative stability. The first field tests of SE fluids were made in 1982, and the fluids have been available commercially for only the last few years.

SE fluids can be regarded as one of the best biodegradable hydraulic fluids. Biodegradability ranges up to 90 percent. They perform well as lubricants. Their liquidity at low and high temperatures is excellent, as is their aging stability. Although they mix well with mineral oils, this characteristic negatively influences their biodegradability. SE fluids offer good corrosion protection and lubricity and usually can be used under the same operating conditions as mineral oils. They are applicable for extreme-temperature range operations and appear to be the best biodegradable fluids for heavy-duty or severe applications. SE fluids are also the most expensive hydraulic fluid, costing up to six times more than mineral-based materials. However, it may be possible to extend oil-change intervals and partially offset the higher cost.

Since SE fluids are miscible with mineral oil, conversion may be accomplished by flushing the system to reduce the residual mineral-oil content to a minimum. Special filter elements are not required. Filters should be checked after 50 hr of operation, as vegetable oil tends to remove mineral-oil deposits from the system and carry them to the filters.

Crop-oil-based lubricants

Rapeseed oil appears to be the base for the most popular of the biodegradable hydraulic fluids. The first RO-based hydraulic fluids were commercially available in 1985. Laboratory tests have identified limits to the use of this oil, but extensive practical experience has yielded relatively few problems.

Opinions on the use of RO vary widely. Its quality has improved over time, and it has become increasingly popular over the past few years, but it has problems at both high and low temperatures and tends to age rapidly. Its cost, about double that of mineral oil, still makes it more affordable than alternative EFLs.

The benefits of RO include its plentiful supply and excellent lubrication qualities. RO is up to 99 percent biodegradable. One popular RO achieves its maximum biodegradation after only

9 days. It offers good corrosion protection for hydraulic systems and does not attack seal materials, varnish, or paint. Mixing with mineral oil is acceptable and has no influence on oil performance. RO is not water soluble and is lighter than water. Escaped oil can be skimmed off the surface of water.

Concerns about RO include poor low-temperature fluidity and rapid oxidation at elevated temperatures. Crop-oil lubricants (including rapeseed, castor, and sunflower oils) tend to age quickly. At high temperatures they become dense and change composition; at low temperatures they thicken and gel. Some RO products are not recommended for use in ambient temperatures above 32 °C or below -6 °C, while other products gel only after extended periods below -18 °C and will perform well up to 82 °C. The major problem with RO is its high content of linoleic and linolenic fatty acids. These acids are characterized by two and three double bonds, respectively. A greater number of these bonds in the product result in a material more sensitive to temperature and prone to rapid oxidation. These problems can be only partially controlled by antioxidants. Refining the base oil to reduce these acids results in increased stability.

Conversion to crop-oil-based fluids should present few problems, as all are mixable with mineral oil. However, contamination with mineral oil should

be kept to a minimum so that biodegradability will not be affected. Special filter elements are not required. Filters should be checked after 50 hr of operation, as crop oils tend to remove mineral-oil deposits from the system and carry these to the filters. Filter-clogging indicators should be carefully monitored, as filter-element service life may be reduced in comparison to mineral-oil operation.

Table 1 shows the significant differences in the oils. Costs do not include the expenses for changing over to the EFL, which may be substantial. PG may require total evacuation of the system plus one or two flushings. Disposal costs for the EFLs will be the same as for mineral oils.

Corps experience to date

Corps Districts were surveyed to determine the extent of EFL use. A follow up with the manufacturers of some of the products revealed that many installations actually were using food-grade lubricants made from synthetic olefins or USP White mineral oils. Neither of these base materials is readily biodegradable.

The highest volume use of products are RO-based biodegradable oils manufactured by Mobil Oil and Texaco, Inc., and used primarily in hydraulic equipment. These companies are major manufacturers in the lubrication

industry. Newer literature indicates Texaco lubrication products are now synthetics and have increased temperature tolerances. The products are being used in the Nashville District in hydraulic power units operating at 14 gpm at 2,500 psi; in the Wilmington District in most hydraulics in their waterfront and floating plant applications; in the Little Rock District in pressure-activated pitch controls in a pumping plant; and in the Alaska District in excavators, cranes, and dredges. Greases and lubricating oils manufactured by Mobil and Central Petroleum Co. are being used in the Nashville District in gate and valve machinery and in the Rock Island District on gate lift chains. Other Districts reported having specified EFLs for specific applications but have yet to place the new equipment in operation. Installations using the products appear satisfied with the performance and are considering expanding their use.

It is suggested that installations considering the use of EFLs should make an accurate assessment of the requirements of the application. EFLs are different from the traditional mineral-based products. Being different does not mean bad, but it does mean that the differences must be given careful consideration. It should not be assumed that a one-to-one substitution can be made without some compromise. The compromise may require a more thorough draining of the system. Different coatings, filters, and seals may be required. Filters may need to be changed more often. Moisture scavengers may need to be added to breather intakes. In new hydraulic systems, it may be advantageous to design larger reservoirs to deal with a foam problem or to make extensive use of stainless steel to deal with corrosivity. The concerns can be addressed, and specific Corps guidance in the form of an engineer technical letter is being prepared by the North Pacific Division.

For additional information, contact Mr. Beitelman at (217) 373-7237.

References

Cheng, V.M., Wessol, A.A., Baudouin, P., BenKinney, M.T., and Novick, N.J. (1991). "Biodegradable and Nontoxic Hydraulic Oils," *Proceedings, 42nd Earthmoving Industry Conference*,

Table 1. Characteristics of Oil Alternatives

Parameter	Oil Type			
	Mineral	Crop	Polyethylene Glycol	Synthetic Ester
Water solubility	low solubility	low solubility	compatible	low solubility
Mixing with mineral oil		possible	not possible	possible
Seal material compatibility	good	good	limited	limited
Varnish compatibility	good	good	limited	good
Low-temperature limit (°C)	-20 to -30	-25	-30	-30 to -40
Price comparison	1	2 to 3	3 to 4	6
Biodegradability (%) ¹	~20	~99	70 to 99	10 to 90
Biodegradability (%) ²	42 to 48	72 to 80	6 to 38	55 to 84

¹ Eichenberger 1991.

² Cheng et al. 1991.

Peoria, IL, 9-10 April 1991, Society of Automotive Engineers Technical Paper Series 910964. (Work was done using the U.S. EPA Shake Flask (Method CS-2000, EPA 560//6-82-003) test procedure.)

Eichenberger, Hans F. (1991).

"Biodegradable Hydraulic Lubricant - An Overview of Current Developments in Central Europe," *Proceedings, 42nd Earthmoving Industry Conference, Peoria, IL, 9-10 April 1991*, Society of Automotive Engineers Technical Paper Series 910962. (Work was done using the European CEC-L-33-T-82 test procedure.)

Alfred D. Beitelman is the REMR Electrical and Mechanical Problem Area Leader and is Director of the Paint Technology Center at the U.S. Construction Engineering Research Laboratory (CERL), Champaign, IL. He received his Bachelor of Arts degree in chemistry from Wartburg College, Waverly, IA. Beitelman developed the Paint Test Kit, a screening device used by both the military and private industry. He has developed many formulations that are used worldwide for painting hydraulic structures.



What's New in Paint

The revised guide specification CWGS-09940, "Painting: Hydraulic Structures," December 1995, has a section to appropriately specify containment structures. This is of particular importance if leaded paints are being removed. The Construction Engineering Research Laboratories (CERL), Champaign, IL, has developed a computer program to help the specifier use this guide specification. The program asks the specifier to select the desired paint system(s). It asks several additional questions regarding containment and then selects all the appropriate paragraphs from the guide and generates an ASCII text file. The file can be read in WordPerfect or most other word processors where the specifier can list the additional requirements necessary for the specific job. Districts wanting a copy of the program may contact CECER-FL-M/A1 Beitelman at (217) 373-7237.

The most recent edition of Engineer Manual (EM) 1110-3-3400, "Painting: New Construction and Maintenance," has a publication date of 30 April 1995. This is a complete revision of the 1980 edition. Many of the subjects covered in the old edition have been revised to include the latest technology. Chapter 11, "Environmental and Worker Protection Regulations," is completely new. It is a quick review of regulations of the Occupational Safety and Health Administration and Environmental Protection Agency as they pertain to painting operations. Many of the regulations are specific for lead removal operations. Paragraphs frequently refer to the specific section of the Code of Federal Regulations (CFR) where requirements are located. Hard copies of the manual should have arrived in District libraries last winter. Copies of this and other U.S. Army Corps of Engineers publications are available

from the National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161 (phone: (703) 487-4650).

The CERL Paint Technology Center is preparing a series of videotapes for paint inspection. Each video is 20 to 30 min long and deals with a specific aspect of civil works painting operations. Two videos, "Preparation for Painting: Surface by Abrasive Blasting" and "Mixing, Thinning, and Applications of Vinyl Paint," have been completed. The video "Evaluation of Applied Coatings" is currently in the review process. Subjects to be covered in future videos include inspection documentation, safety, metallizing, epoxy paints, and containment structures. Copies of completed videos are available on loan from CECER-TR-PA/Dana Finney at (217) 352-6511, ext. 7386.

Annual Field Review Group Meeting To Be Held in August

The 8th REMR-II Field Review Group Meeting will be held at Waterways Experiment Station, 13-14 August 1996. Representatives from all Districts and Divisions are encouraged to attend. The meeting will be open to the public as well as to Corps personnel involved in the repair, evaluation, maintenance, and rehabilitation of the Nation's infrastructure. For additional information, contact Lee Byrne, CEWES-SC-A, 3909 Halls Ferry Road, Vicksburg, MS 39180-6199, or call (601) 634-2587 (e-mail: byrnee@ex1.wes.army.mil).

Seismic Strengthening of Hotel Oakland Revisited: A Case Study

by Edward F. O'Neil, U.S. Army Engineer Waterways Experiment Station

(Adapted from Edward F. O'Neil, 1995, "Repair and Maintenance of Masonry Structures: Case Histories," Technical Report REMR-CS-46, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS).

The Loma Prieta earthquake that hit northern California on October 17, 1989, measured 6.9 on the Richter scale. The intensity of the quake was quite severe in downtown Oakland, which lies 20 miles east of the San Andreas Fault, and many unreinforced masonry structures were badly damaged. However, the Hotel Oakland survived with only architectural damage to the exterior and interior walls. The fact that the damage sustained was minimal can be attributed to seismic strengthening made in 1979 during conversion of the building into an apartment complex for the elderly.

The architects and engineers who had renovated the structure in 1979 were again retained to restore the building to its full use. During these repairs, this team had the rare opportunity to study the effectiveness of the strengthening they had made 10 years previously.

History of the Hotel Oakland

Originally constructed between 1910 and 1912 with funds exceeding \$3,000,000, the block-square hotel

(Figure 1) became a prominent social center during the next decade. Presidents Wilson, Coolidge, and Hoover were guests at the facility, as were other celebrities, including Amelia Earhardt, Sarah Bernhardt, Jean Harlow, and Mary Pickford (Scott 1959).

During the 1930's, the hotel was forced into bankruptcy several times as the result of the depression and management difficulties. In 1943, the U.S. Army took possession of it for use as a hospital. All furnishings were auctioned off, including irreplaceable chandeliers of which only photographs remain. Following World War II, several unsuccessful attempts were made to reopen the hotel for public use. The Veterans' Administration eventually occupied the facility as a hospital until August 1963. For the next 15 years it stood vacant. In 1978 a Boston-based developer obtained possession and remodeled it into a housing project for the elderly. It remains in this use today.

National Register of Historic Spaces

Currently, the exterior of the building and all two-story spaces on the main floor are on the National Register of Historic Spaces. These grand, ornately

decorated rooms include the main entrance lounging room; the Corinthian-columned, 5,000-ft² ballroom; the dining room; and the cafe, which has 30-ft-high oak-paneled walls and a finely detailed plaster ceiling.

Original construction

The building was designed as a steel-frame construction with a reinforced-concrete foundation supported on spread footings on sandy-silty material at the basement level (Wooser 1981). Reinforced concrete was also used for the floor slabs. The columns were fabricated of Bethlehem Steel "H" sections. The exterior 13-in.-thick walls were nonload-bearing and consisted of three wythes of brick. The face brick was described as Carnegie Pressed Brick of a creamy-beige color. Brick was used to fireproof the columns, while concrete encased the beams and girders. All partitions in the building were of hollow clay tiles covered with a plaster finish.

1979 restoration

After the 1979 earthquake, a survey of the structure indicated that the steel frame and concrete foundations were in good shape. The building had been designed to resist wind forces, but it fell far short of complying with seismic code requirements. The unreinforced exterior brick walls were especially subject to failure in an earthquake. Of prime importance in the rehabilitation of the hotel was the need to develop a cost-effective system of earthquake bracing that would reduce the life-safety hazard.

The survey indicated two major deficiencies in earthquake situations: the first was the potential for brick-wall collapse and the second was the need for major vertical shear walls throughout the building to strengthen it. Although steel buildings do not usually collapse in an earthquake, unreinforced masonry walls do; so the three-wythe brick walls of the hotel had to be tied to the steel

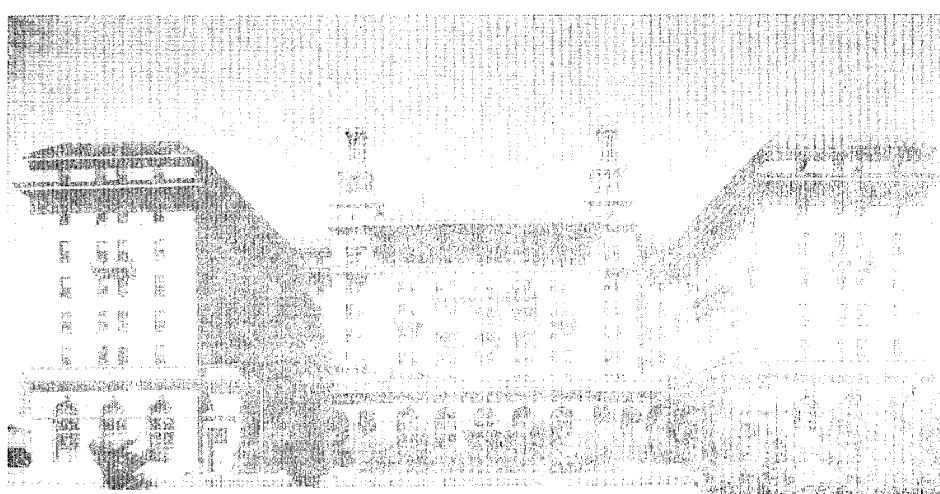


Figure 1. Hotel Oakland

frame to guard against collapse and detachment from the steel framework.

Solutions

The purpose of the renovation was to develop a maximum number of one-bedroom and efficiency apartments for the elderly. At the same time, it was determined that the building should be reinforced to reduce life-hazard exposure to a minimum in the event of an earthquake. The evaluation indicated that the building provided resistance to 60 percent of the forces required by the 1973 California Uniform Building Code. The limitation to 60 percent was controlled by the overturning forces, but in many respects the structure had the capacity to resist much higher forces.

The frame added significant seismic-resisting capability to the building and provided a completely independent system for support of gravity loads. The steel frame acted as a backup system and provided additional ductility, continuity, and redundancy to the structure. No building with a complete structural steel frame has been known to collapse in an earthquake. Significant experience with similar structures was gained during the 1906 earthquake in San Francisco, where numerous steel-frame buildings over 10 stories in height survived with reportedly little earthquake-induced damage.

The renovation plans stipulated that all interior walls from roof to basement would be demolished. Exceptions to this decision were the concrete floors, the exterior walls, and the historical rooms. Removal of the hollow clay tile partitions, which would shatter in an earthquake, eliminated substantial seismic hazard (Figure 2). This removal also reduced the total mass of the building, thus lowering the effective earthquake inertia forces.

Strengthening of the brick walls

The exterior brick was part of the historic charm of the building, and any attempt to replace it with another cladding would have been prohibitively expensive. Therefore, one of the requirements in the repair solution was that this brick would remain.

Because of their great length, the existing brick walls provided stiffness to the building to resist minor and moderate earthquakes, but major earthquakes could cause severe damage to the brick. In resisting lateral forces whether from wind or earthquake, the brick walls had to resist forces normal to their surface as well as those produced in the plane of the wall. That is, they had to be able to resist floor-to-floor normal forces and act as shear walls for in-plane forces. At low force levels, brick walls have the capacity to do this. However, major earthquakes create stresses that will exceed the brick strength, particularly for out-of-plane bending. The shear-wall response is complicated by the number of openings in the walls (i.e. window openings), which subject piers and spandrels to flexural as well as shear stresses.

In an effort to determine the shear strength of the existing masonry, bead-joint shear tests were performed on 6-in.-diam cores removed from the exterior walls. The 15 samples tested showed an average shear strength of 50 psi. The testing indicated that the walls were not designed for resistance to the high force levels experienced in an earthquake. However, if the brick walls could be held in place, they would be effective even after major cracking since the crushing of the brick along fracture surfaces during earthquake movement would absorb a great deal of energy. To this end, a basketing system was

developed to stabilize the brick walls if cracking occurred.

The system devised was incorporated into the new wall furring that was applied within the steel frames of the exterior walls (Figures 3 and 4). Heavier structural studs were mixed in with the basic stud-furring system and were spaced so that wall anchors could be secured on approximately 3-ft centers in both vertical and horizontal directions. The wall anchors were 1/2-in.-diam bolts that were long enough to extend from the structural studs through the two interior wythes of the exterior wall and into the face brick. The bolts were inserted into the wall through holes drilled into the brick to a depth including partial penetration in the face brick. They were then anchored to the brick with polyester-resin epoxy cartridges.

Prior to the actual use of this system, tests were conducted to determine the strength of the epoxied bolts in the brick. Three anchors were epoxied into brick test panels and were loaded to failure. One failed at 7,500 lbf, and the other two at 9,000 lbf, with all failures occurring in the anchor, not in the brick or in the bond between the brick and the anchor. There were 4,900 bolts used in the wall renovation, and 520 of these bolts were subjected to pullout testing. The anchors were loaded to a magnitude of 1,000 lbf and held at that level for 1 min. Only 34 anchors failed the proof loading.



Figure 2. Clay tile partition rubble from 1979 renovations

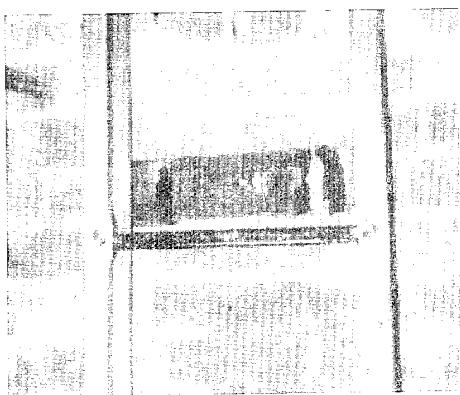


Figure 3. Structural studs and wall anchor

To complete the wall anchorage, the bolts were attached to plates that spanned adjacent structural studs. The stud system then provided a positive anchorage detail to the floor framing above and below. Thus, the exterior wall system was reinforced with steel studs having the capacity to brace the walls against out-of-plane forces after failure of the brick. The system was intended to hold the brick in place, reduce potential falling hazard, and use the crushing of the brick during an earthquake for its energy-absorbing value.

Shear-wall strengthening

Reinforcement of the exterior brick walls was important to the performance of the building in an earthquake, but it was only part of the story. To provide additional strength and ductility to resist major earthquakes, a new system of reinforced-concrete shear walls was designed to be added around the stair and elevator shafts (Figure 5). This system was well distributed around the building in the upper stories and was supplemented by additional shear walls from the second floor down to the foundations.

Several functions were served by this system: the needed seismic shear resistance was provided by the new walls; the shafts (stairwell, elevator, etc.) would remain accessible and operable (free of debris that would result from use of a more brittle material); and a 4-hr fire-resistive environment was provided in the shafts.

The new shear-wall system worked well within the confines of the existing structural framing system. The walls

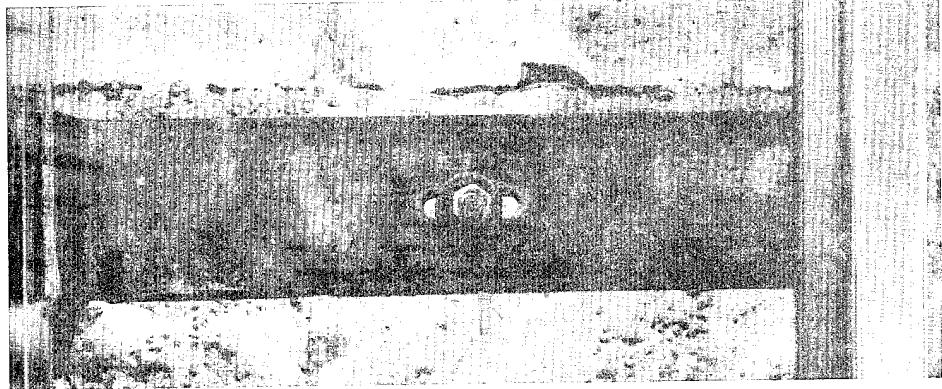


Figure 4. Detail of basketing anchor

were tied into steel floor beams, which served as collectors to deliver diaphragm forces, and into the steel columns, which acted as chord members to resist the tension and compression from the cantilever action of the wall. Nelson studs were added to the existing structural steel members to develop the forces. The new walls were reinforced for the shear stresses and for resistance of net tension forces at the steel columns, supplementing the capacity of the column splices.

The most critical aspect of the shear-wall design was the overturning effect. Although the interior stresses within a shear wall were readily accommodated, enough gravity load had to be mobilized in the walls to enable them to resist overturning. To this end, the walls were tied into the load-carrying columns in the upper stories. In the lower stories, the walls were extended to embrace adjacent columns, creating a bigger base and providing stability for each shear-wall setup to resist overturning effects. In areas where the existing steel columns could not transfer all the uplift into the foundations, additional reinforcing steel was provided, and the new foundations were interconnected with the existing footings to provide a new composite system.

1989 Loma Prieta earthquake

During the 1989 Loma Prieta earthquake, the structure performed as the engineers anticipated. While the measures taken had not brought the building up to current codes or

structural standards, they did provide a life-safety performance level that prevented collapse and protected human life.

Shortly before the 1989 earthquake, the hotel had been acquired by a local real estate development firm with a long history of successful rehabilitation development. Two days after the quake, the new owners contacted the architects and engineers who had renovated the building in 1979. In assessing the damage and estimating the costs of repair, the owner and design team enlisted the assistance of an experienced general contractor. The architects, engineers, and general contractor worked as a team from the initial investigation until completion.

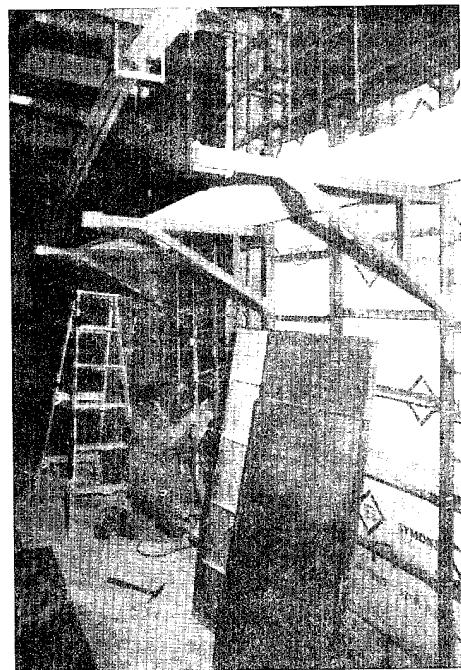


Figure 5. Forming for interior shear walls

Although the 1989 Loma Prieta earthquake did no damage to the integrity of the structure, there was considerable architectural damage to the exterior brick masonry walls and to a number of apartments. Substantial amounts of brick had fallen to the street from the southwest corner of the building, exposing some of the apartments and the steel framing (Figure 6). Except for 30 apartments, the remaining 185 units could be occupied while the remaining units were being repaired.

Structural damage

The most significant damage sustained by the hotel was cracking of some of the exterior brick walls. Although not load-bearing, these brick walls were the stiffest elements in the building, and they resisted the main thrust of the earthquake force. The damage was manifested as diagonal (X) cracks in the wall piers with virtually no cracking in the horizontal spandrels (Figure 6).

In the most severely damaged wing, the cracks were over 1/2 in. wide, with complex fracturing through the entire thickness of this wall. There were also areas where the face brick had fallen and other areas where it was loose. The damage in this area was enough to create a potential life-safety hazard that could not be ignored. An aftershock could dislodge portions of the wall that could fall on people below. It appeared that the brick in this area would have to be removed and replaced.

Only very minor damage (hairline cracks) occurred in the reinforced concrete interior walls constructed in 1979. Additional cracks were reported in the concrete floor slabs and may have been a result of the earthquake.

It is interesting to note that during the 1979 renovations, reinforced concrete stair towers were built into both the east and west wings of the building. In the east wing, the stair tower was built with its longitudinal axis perpendicular to the longitudinal axis of the wing itself or parallel to the facade of the end wall of the wing. In the west wing, where the major brick damage from the 1989 earthquake occurred, the stair tower had been built with its longitudinal axis parallel to the longitudinal axis of the wing due to space considerations. The east wing

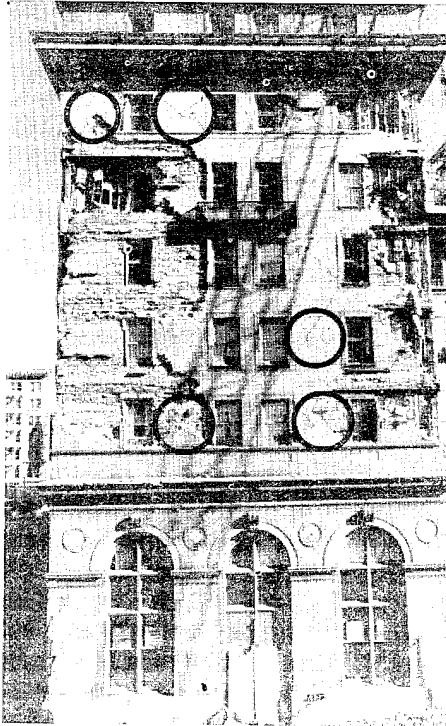


Figure 6. Damage to southwest facade after removal of loose brick

experienced significantly less damage to the brick facade as a result of this additional stiffening.

The corner areas of the building where the wings meet the main body of the building were damaged, especially in the upper floor. The concrete floor slabs exhibited some cracking starting at the corner and extending into the main floor area. The steel floor framing in these areas did not line up directly with the walls and allow for a direct load path between the floor diaphragms and the walls. To strengthen the floor slab, new steel drag elements were added to interconnect the steel framing below the slab; this would relieve stress concentrations in the slabs and help collect and deliver the tributary loads to the new shear walls.

Seismic strengthening system

In consultation with building department officials, the owners decided that the new strengthening elements of the building would be designed to meet 75 percent of the current Uniform Building Code design force level for new buildings. The owners were interested in fulfilling the requirements of the local building officials and in

providing further assurance of life safety to the occupants. In addition, the new strengthening measures had to consider the historic character of the building.

The structural strengthening system was designed to provide seismic resistance within the confines of reinforced-concrete walls arranged in a relatively uniform manner to minimize diaphragm stress and earthquake forces on the brick walls. In areas where the concrete walls were damaged, new reinforced-concrete walls were added to the inside face of the exterior brick walls such that total resistance was provided by the new and existing reinforced concrete.

In the first-story historic spaces, the strengthening walls were located behind the existing historically sensitive wall surfaces to keep the architecture of the space clean (Figure 7). In the upper stories, the additional wall thickness encroached into the living spaces, and the apartment units had to be remodeled (Figure 8). The work space for placement of the new concrete shear walls against the existing brick was very tight; therefore, the contractor devised a resourceful forming system. Stay-in-place formwork was used and held in place by metal studs that were in turn supported by steel dowels carefully placed and epoxied into the facia brick. The studs supported the forms and anchored the brick to the new concrete walls. The studs were stiffened by wood blocking at each stud and laterally supported by whalers. This method allowed observation of the concrete placement through the formwork and greatly simplified and accelerated the process. The metal studs that remained in place were used as furring for the interior finishes, so there were no forms to remove, only the wood blocking and whalers.

Because of the landmark status of the hotel, the new shear walls had to accommodate the existing window and door openings. Historic preservation considerations did not allow for filling the door and window openings, so a solution was needed that could meet these constraints. The concrete shear-wall detailing provisions of the Uniform Building Code require tightly tied reinforced boundary elements in the walls and diagonal shear reinforcing in some of the spandrel beams between the window openings. To reduce some of the reinforcing requirements and to

minimize construction costs, higher strength concrete was specified in these shear walls.

Where the brick wall was removed, a reinforced concrete wall was constructed and finished with brick veneer to match the existing brick work. Major new foundation work was required to carry the additional weight of the new concrete walls and, more importantly, to resist the overturning effects of earthquake forces.

The exterior brick walls required significant work to repair the cracks caused by the earthquake. The cracks were injected with epoxy to restore original strength, and the finish was then patched to match the adjacent surfaces as closely as possible. The restoration process was complicated by the effects of cleaning on the existing material and on the new face brick and mortar.

The seismic strengthening system for the Hotel Oakland was selected only after several alternative systems had been considered, including steel bracing, interior shear walls, and shotcreting the entire exterior wall system. The final choice was based on a combination of structural effectiveness, minimal disturbance to the residents, preservation of historic significance, and relative cost, including cost of displacement.

The architectural and engineering work and the construction documents were completed in mid-1991. Financing was in place and the construction loan closed in early 1992, with construction starting shortly thereafter. Construction was completed in August 1993.

Performance to date

This project has afforded a unique opportunity for observation of the performance of a seismically



Figure 7. Strengthening of walls behind historical facades



Figure 8. Strengthening of typical upper floor walls

strengthened historic building in an earthquake and to confirm that criteria used in earlier work have performed as projected. It also presented the challenge of revisiting the damaged building and working within the constraints of current codes, modifying it for prevailing structural code compliance, for life-safety, and within an affordable budget.

A total of 315 apartments were developed, including a portion of the ground floor and the mezzanine floor. At completion, 272,000 ft² of residential floor area has been remodeled at a cost of \$11.8 million, averaging \$44/ft²; 315 efficiency and one-bedroom apartments have been created; and 50,000 ft² of first-floor public space has been

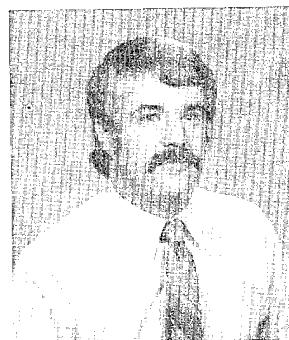
developed, part of it for tenant use and part to be historically restored for leasing as commercial space.

This effort demonstrates the importance of consistent and cooperative effort between a developer with development and financing expertise, a contractor who can successfully work with the unknowns and complexities of an old building in constructing new concrete shear walls in almost inaccessible locations, and an architect-engineer team with the knowledge and technical ability to creatively solve the attendant problems.

Photographs included in this article are courtesy of the Roberts-Obayashi Corp., Danville, CA.

For additional information, contact Mr. O'Neil at (601) 634-3387.

Ed O'Neil is a research civil engineer in the Engineering Mechanics Branch, Concrete Technology Division, Structures Laboratory, WES. He holds a B.S. degree in civil engineering from Northeastern University and an M.S. degree in civil engineering from Purdue University. He has been involved in structural research for the Department of the Air Force, the Huntsville Division under the National MAGLEV Initiative, and other WES divisions and laboratories. He is the WES point of contact for the management of the WES Field Exposure Station at Treat Island, Eastport, ME. O'Neil is a member of the American Concrete Institute, Society of American Military Engineers, and the Posttensioning Institute.



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ROBERT W. WHALIN, PhD, PE
Director

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